UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

eRD18 - Precision Central Silicon Tracking & Vertexing for the EIC

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eRD18: Proposal

To develop a detailed concept for a central silicon vertex detector for a future EIC experiment, exploring the potential advantages of HV/HR-CMOS MAPS technologies

Physics motivation

Open heavy flavour decays – **high position resolution**

Precision tracking of high Q^2 scattered electrons – **low mass**

WP1: Sensor Development

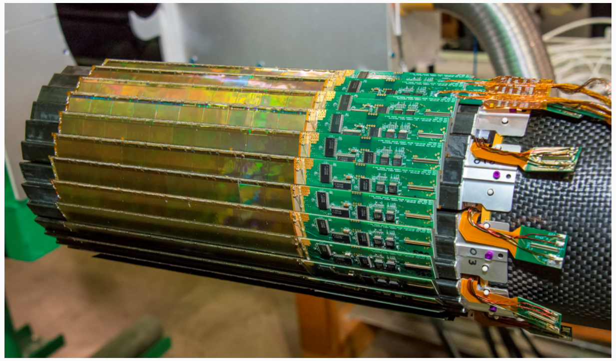
Exploit on-going R&D in Birmingham into HV/HR-CMOS MAPS to investigate potential solutions for the EIC

WP2: Silicon Detector Layout Investigations

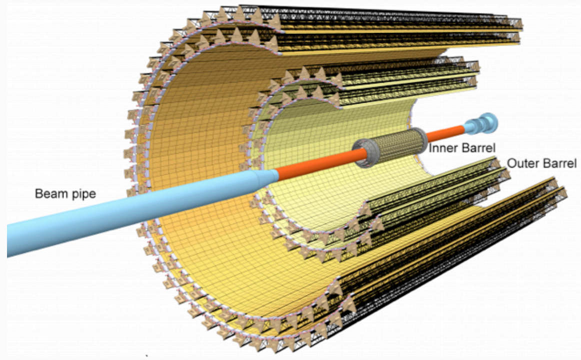
Performance requirements: numbers of layers, layout and spatial resolution of the pixel hits

Background: State-of-the art MAPS

STAR Heavy Flavour Tracker (HFT) at RHIC

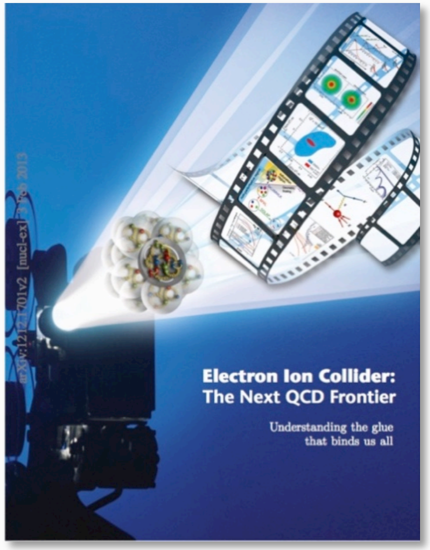


ALICE Inner Tracking System (ITS) Upgrade at LHC



- Key features of MAPS
  - Small pixel size (down to 20 µm x 20 µm)
  - Low power (< few hundred mW/cm^2)
  - Low material budget (~ 0.3% X_0 per layer)
  - Moderate radiation hardness (~Mrad, 10^{13} 1MeV n_{eq}/cm^2)

Charm observables in the EIC White Paper



A. Accardi et al.,
Eur. Phys. J. A (2016) 52:268

- Leading order charm production process is γg fusion

- Provides sensitivity to:
  I. The gluon contribution to spin of the nucleon
     - Charm sensitive to Δg in e-p scattering
  II. Physics of high gluon densities and low-x in nuclei
     - Measurement of F_2^{charm} sensitive to nuclear gluon density in e-A
  III. Hadronisation and energy loss in cold nuclear matter
     - Nuclear modification and quark mass dependence

- A future EIC promises unprecedented precision in charm (and beauty)
  – Reconstruction challenging due to short decay lengths ~ 100 μm
  – Likely to place strongest constraints on the tracker design
  – Potential importance of low-p_T (standalone) tracking

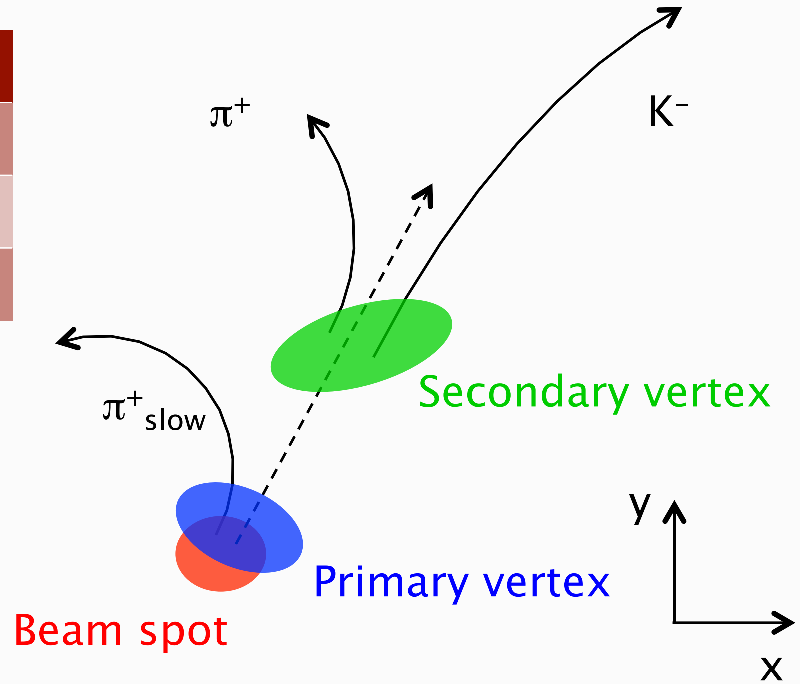
Open charm reconstruction

- Signature is displaced (secondary) decay vertex

Particle	Decay	Branching	$c\tau$ [μm]
D^0	$K^-\pi^+$	3.9%	123
D^+	$K^-\pi^+\pi^+$	9.5%	311
D^{*+}	$D^0\pi^+_{slow}$	67.7%	

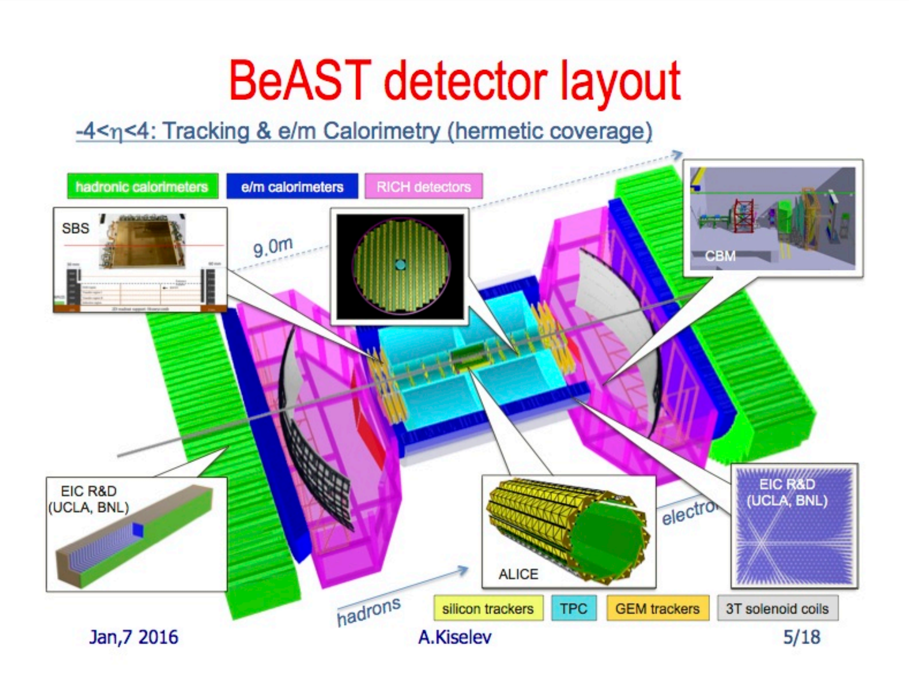
Example:

$$D^{*+} \to D^0\pi^+_{slow} \to \left(K^-\pi^+\right)\pi^+_{slow}$$

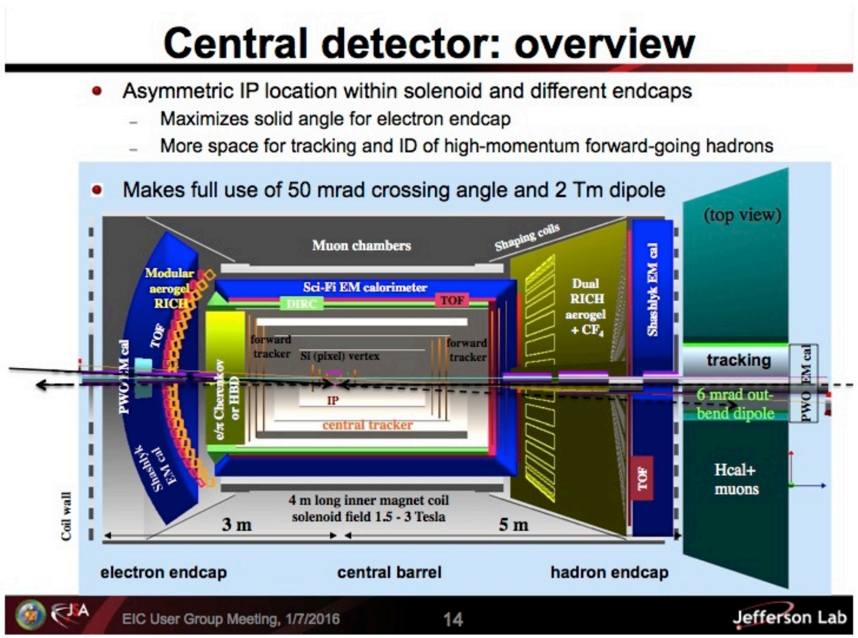


- Requires excellent impact parameter resolution in r-ϕ and z
  - Dominated by position and resolution of innermost tracking layer
    - Close as possible to beam pipe (caution: radiation environment)
    - Highest possible spatial resolution (small pixels)

Background: EIC Detector Concepts



Alexander Kiselev



Pawel Nadel-Turonski

Based on **ALICE ITS** upgrade

Several technology options, e.g. **Belle II** DEPFET-based pixel **SVD**

- Si vertex and tracker detectors in central and forward regions
- Seek high resolution, high s/n, low mass, low power solution
  - applicable to both eRHIC and JLEIC

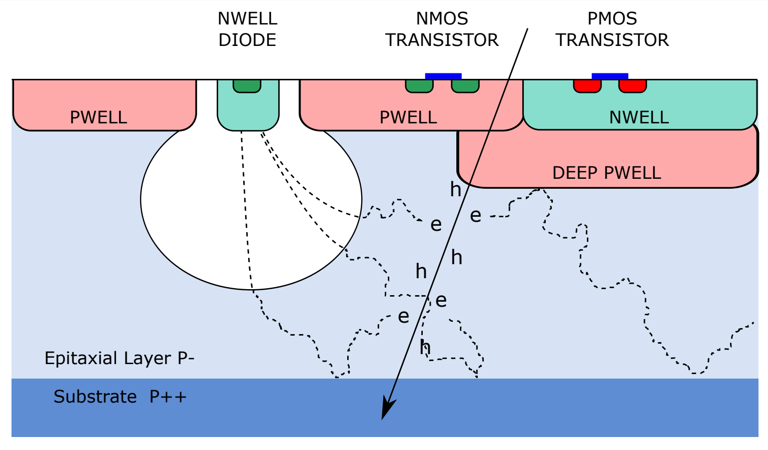
WP1: Sensor development

- Aim: to demonstrate *high spatial resolution* in a *fully depleted* sensor
  - Advantage of depletion = charge collection by drift
    ➔ larger Q, fast collection, small cluster multiplicity, rad. hardness

- Starting point: ALPIDE sensor (ALICE ITS)
  - Partially depleted; charge collection in part by drift
  - Small collection electrode = low detector capacitance
    ➔ low power, low noise, low crosstalk, fast readout

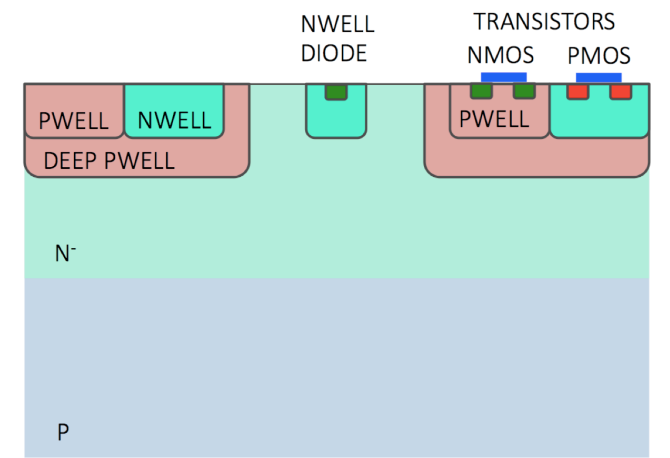
ALPIDE sensor
- 0.18 μm CMOS TowerJazz
- 28 x 28 μm^2 pixel pitch
- <2 μs time resolution
- Power density < 50 mW cm^{-2}
- 50 kHz interaction rate (Pb-Pb)
- 200 kHz interaction rate (pp)

ALICE- ITS
Inner layer thickness = 0.3% X_0
Outer layer thickness = 0.8% X_0



WP1: Sensor development

- R&D strategy: maximise Q/C
  - Investigating two commercial HV/HR-CMOS technologies to achieve larger depleted volume: TowerJazz and LFoundry
- TowerJazz "modified" process
  - CERN-TowerJazz (CERN-TJ) collaboration: 180 nm process with additional planar junction deep in the epitaxial layer
  - First results* indicate full depletion; larger signal with faster and more uniform charge collection wrt standard process
  - Small collection electrode, so low detector capacitance like ALPIDE



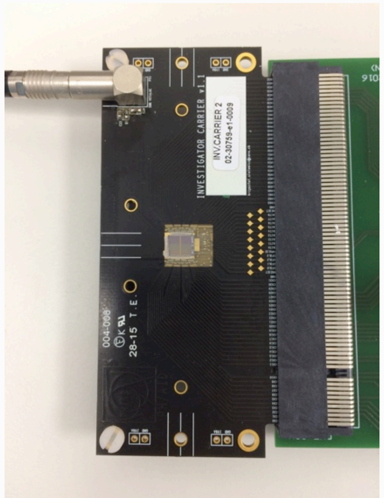
Modified pixel structure

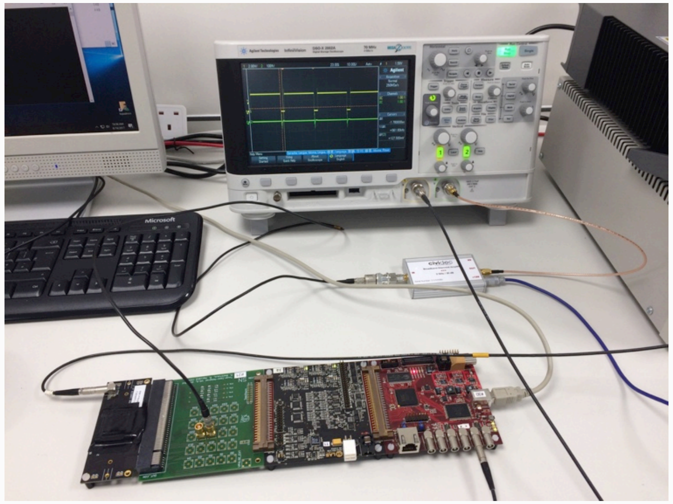
We believe this technology is a strong contender for a dedicated **EIC MAPS prototype**

*H. Pernegger et al., First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors, 2017 JINST 12 P06008.

WP1: Sensor development

- CERN-TJ investigator chip now available for testing in Birmingham
  - Designed to study charge collection properties and detection efficiency
  - More than 100 pixel matrices (10 x 10 pixels)
  - Range of pixel sizes relevant to both EIC barrel and disks
    - 20 x 20 μm^2 to 50 x 50 μm^2 pixels
  - Simple follower-based (analogue-only) readout
  - Characterisation of the sensor will be our focus in FY18
    - Focusing on matrices with small pixels





WP1: Sensor development

- Other developments
  1. Prototype submitted in May in TowerJazz standard process
     - Part of a separate Digital ECal (DECAL) project (UK funded PRD)
     - Uses larger pixels and multiple collection electrodes to match requirements of DECAL chip design
     - Not presently being considered for EIC studies
  2. Submission of test structures in TowerJazz modified process
     - Multi-Project Wafer submission with CERN in July
     - Consists of larger pixels with multiple small collection electrodes to complement investigator chip structures
  3. RD50 LFoundry submission expected by end of the year
     - Matrices with **improved time resolution** (in-pixel TOA and TDC)
     - Test structures with pixels down to 20 x 20 μm^2
     - But, large electrode (electronics sits within the collecting n-well)

  Options 2. and 3. are useful for evaluation purposes

  ➔ Large Q, but also larger C than single small electrode

WP1: Sensor development

- Work plan for FY18
  1. Characterisation of the CERN-TJ investigator chip
     - Parameters to evaluate: signal amplitude and response time
     - Tests with radioactive sources (^{55}Fe and ^{90}Sr) and laser eTCT setup

       Calibration, measurement of depletion width, uniformity of charge collection between pixels
     - Irradiations at MC40 cyclotron with 28 MeV protons
     - Possible participation in test beam with colleagues at CERN to study detection efficiency
  2. TCAD simulations
     - Evaluate optimal electrode configuration, epitaxial layer resistivity, with inputs from results of characterisation
  3. EIC MAPS specifications and design
     - Define specifications for EIC specific sensor
     - Possibly start discussing design options with chip designer

eRD18 and eRD16: Toward an EIC specific sensor

- Factors affecting readout architecture
  1. Interaction rate and pixel occupancy
     - eRHIC: coll freq = 28.2 MHz (35.5 ns bunch spacing)
     - JLEIC: coll freq = 476 MHz (2.1 ns bunch spacing)
  2. Time resolution
     - Limited by pre-amp rise time (analogue power density)
     - Important to have small detector capacitance

	ALPIDE	MALTA	HGTD
Pixel size	28 x 28 μm^2	36 x 36 μm^2	1 x 1 mm^2
Analogue power	5-6 mW/cm^2	50-60 mW/cm^2	100 mW/cm^2
Time resolution	2 μs	25 ns	40 ps

  3. Readout speed
     - Triggered versus untriggered readout, on-chip buffering, speed of output links, clock distribution – all drive digital power density

➔ Time resolution and readout speed impact mass and granularity

eRD18 and eRD16: Toward an EIC specific sensor

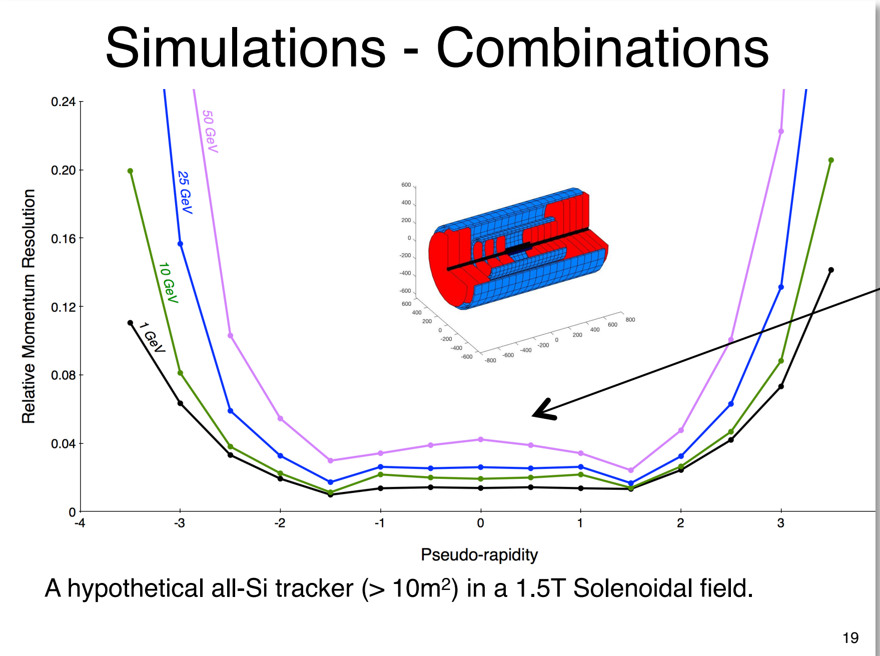
- EIC sensor readout
  - Two possible scenarios – depending on required tracking performance
    1. Design sensor with required spatial **and** time resolution in all layers
    2. Develop a faster, lower granularity sensor for the outermost layer
  - Possible synergy with eRD6 – Tracking Consortium
    - Joint interest in developing a fast timing / trigger layer
- Future roadmap in collaboration with eRD16
  - Two video meetings to discuss developments and future plans
  - Collaborating on layout simulations, using the same geometry descriptions
  - Divide work according to physics observable (electrons vs heavy flavour)
  - Placement of first disk layer(s) may have impact on barrel performance
  - Iterate toward a final set of requirements for barrel and disks in FY18
  - Aim to design and submit an EIC specific sensor prototype in FY19
  - Potential to build a silicon (MAPS) consortium at that stage

WP2: Simulations

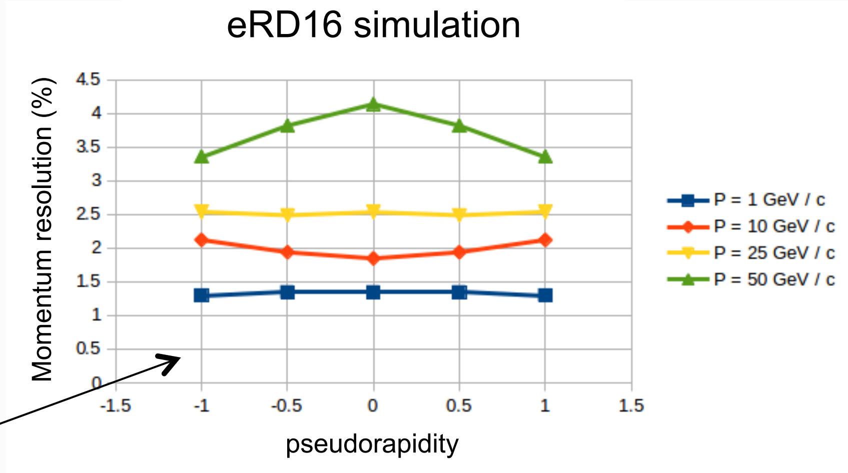
- Planned for new postdoc to work on simulations (and sensor tests)
  - 0.5 FTE funded through EIC R&D funds
  - Post filled by Dr. Sam Bailey; started on 1st March
  - Focus on simulations in EicRoot software framework
- Initial tests with standalone tracker to make connection with eRD16
  - Studied electrons with two barrel configurations:
    - Default 4-layer barrel (2.3, 4.7, 14, 16 cm)
    - ALICE-ITS-like 7-layer barrel (2.3, 3.1, 3.9, 20, 25, 34, 39 cm)
    - All layers 0.3% X_0; 6 μm spatial resolution (20 μm pixels)
- Subsequent tests have focused on combined Si barrel plus TPC
  - Studied pions (kaons and protons) from 500 MeV/c to 10 GeV/c
  - Various barrel configurations plus default TPC specification
  - 4-layer barrel, default geometry, 20-40 μm pixels
  - 3, 4 and 5-layer barrels, 30 μm pixels
  - 4 and 5-layer barrels with 350 μm pixels in outer layer (on-going)

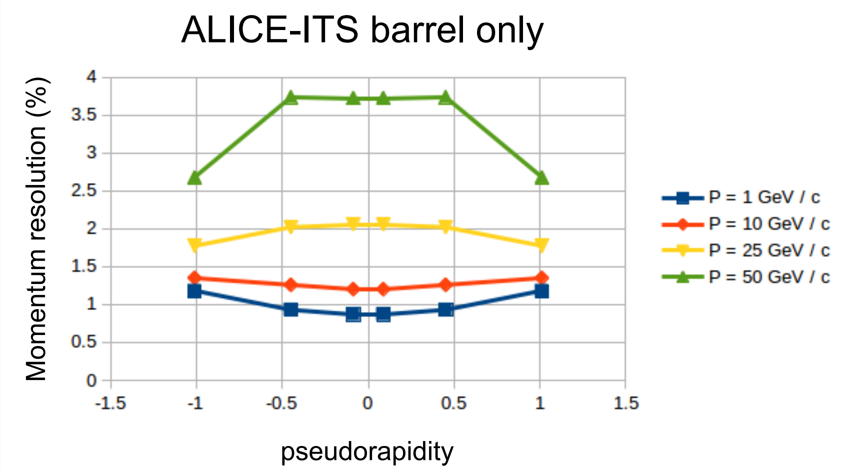
WP2: Simulations

- Results: electrons in a standalone silicon tracker



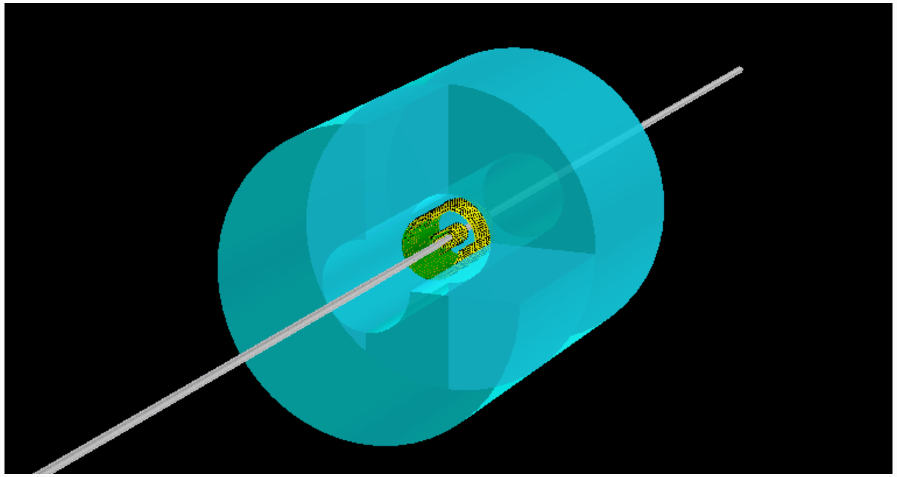
Ernst Sichtermann – eRD16, January 2017

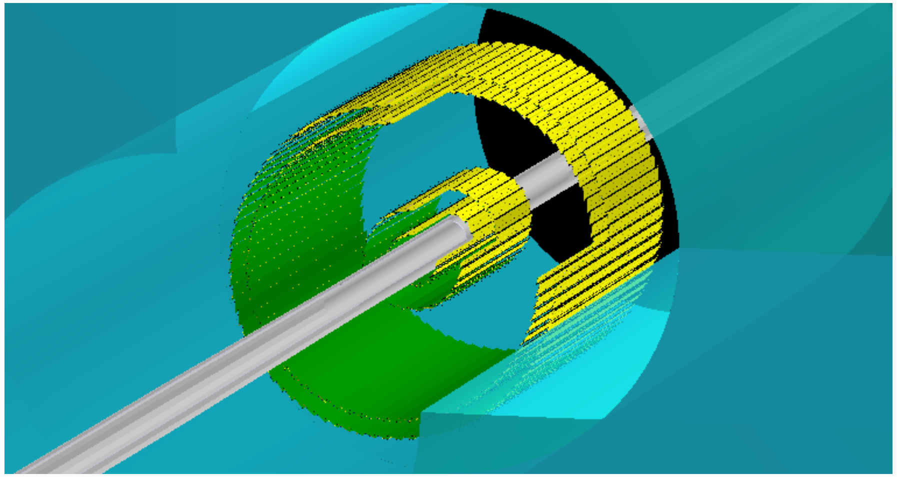




WP2: Simulations

- Geometry: TPC + VST + beam pipe + magnetic field (B = 0.5 T)





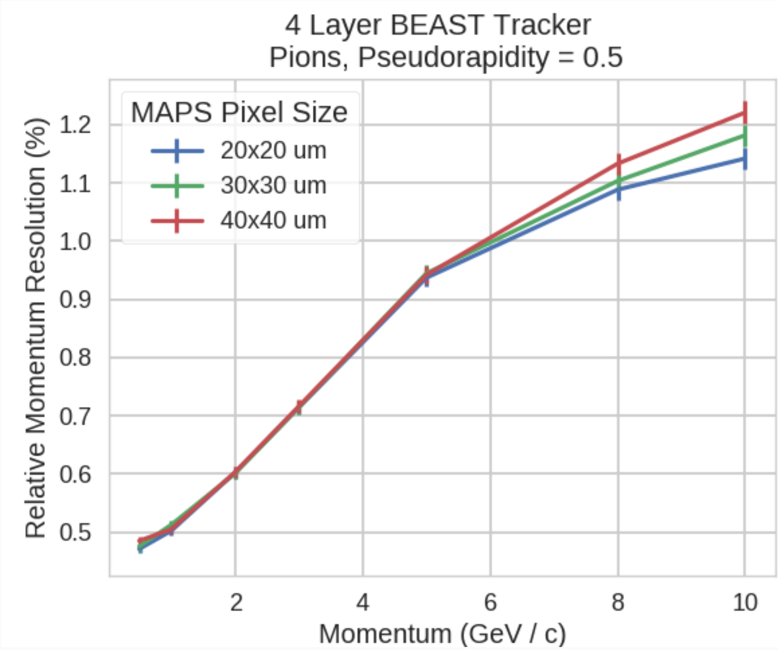
TPC parameters
Inner radius = 20 cm
Outer radius = 80 cm
250 μm position resolution

VST parameters
Layer #1 radius = 2.3 cm
Layer #2 radius = 4.6 cm
Layer #3 radius = 14 cm
Layer #5 radius = 16 cm
30 x 30 μm pixels
0.3% X_0 per layer

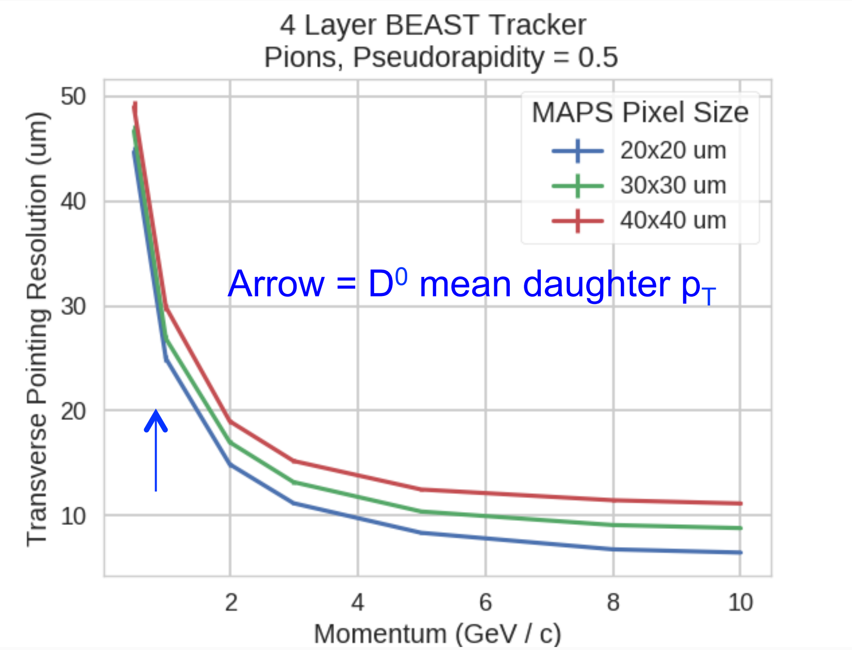
Beam pipe parameters
Material = beryllium
Outer radius = 1.8 cm
Thickness = 0.8 mm

WP2: Simulations

- Results: pions; eta = 0.5; 3 pixel sizes: 20 μm, 30 μm and 40 μm



Relative momentum resolution (%)
versus momentum

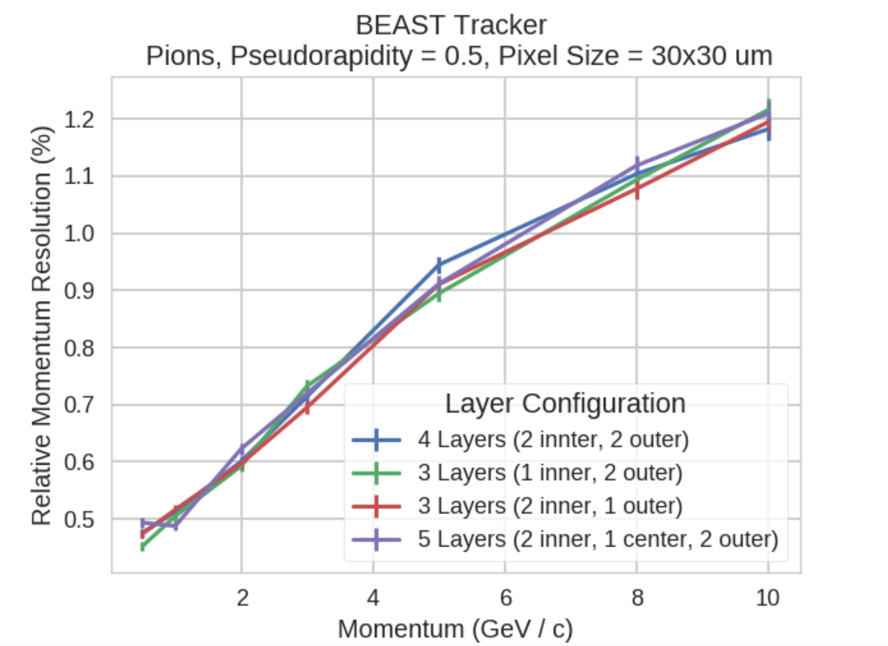


Impact parameter resolution (μm)
in transverse (r-ϕ) plane
versus momentum

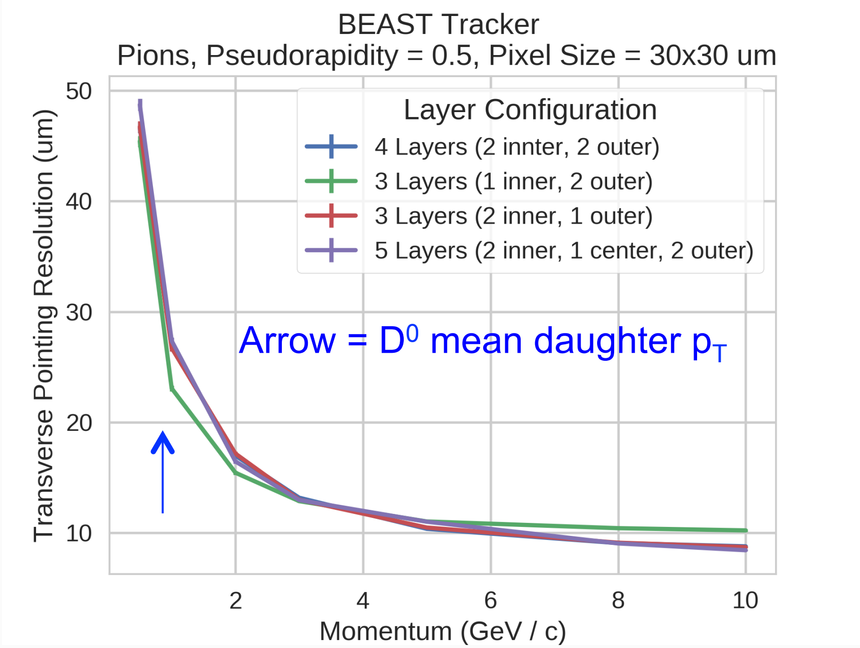
- Modest improvement in impact parameter resolution for all p_T
  - Dominated by resolution of innermost layer

WP2: Simulations

- Results: pions; eta = 0.5; pixel size = 30 μm; 3, 4 and 5 layers



Relative momentum resolution (%) versus momentum



Impact parameter resolution (μm) in transverse (r-ϕ) plane versus momentum

- Little sensitivity to the number of layers
  - Slightly better impact parameter resolution with one inner layer

WP2 Simulations

- Work plan for FY18
  1. Tracker characterisation
     - Complete study of single track **momentum resolution** and **impact parameter resolution** based on different assumptions on **the pixel dimensions** and **number** and **thickness** of tracking layers
  2. Tracker optimisation
     - Optimise separation of tracking layers
     - Explore tradeoffs in scenarios with different **pixel sizes** and **layer thicknesses** in different layers

       e.g. fast timing layer
     - Study standalone tracking performance at low p_T

Scope and deliverables

- Scope
  - Second year of a two-year initial design study
  - By the end of FY18 we aim to have defined a set of requirements necessary to design an specific EIC sensor
- Deliverables
  - WP1: Characterisation of pixel matrices in CERN-TJ demonstrator
  - WP1: TCAD simulations to optimise pixel geometry and aspect ratio
  - WP1: Begin to explore charge collection properties and timing characterisatics with input from sensor designer
  - WP2: Complete study of single track momentum resolution and impact parameter resolution based on different assumptions on the pixel dimensions and number and thickness of tracking layers
  - WP2: Optimise tracking layer separation and explore tradeoffs in scenarios with different pixel dimensions in different layers
  - eRD18 with eRD16: Initial sensor specifications for disks and barrel

Resources summary

- Existing resources
  - Staff effort: Gonella (0.2 FTE), Jones (0.1 FTE), Newman (0.05 FTE), Allport (0.05 FTE)
  - Access to CERN-TJ investigator chip
  - PhD student (Håkan Wennlöf) from October 2017
  - Access to MC40 cyclotron for irradiation studies
- Requested resources
  1. PDRA (1 FTE) = £107k ($150k) to work on WP2 (60%) and WP1 (40%)
  2. Travel (4 x 2 x £1,250) = £10k ($14k)

Scenario	PDRA	Travel	Total (GBP)	Total (USD)
100%	£107,394	£10,000	£117,394	$164,352
80%	£83,915	£10,000	£93,915	$131,481
60%	£60,436	£10,000	£70,436	$98,611

Note: Input from sensor designer might be useful toward end of the project

Backup: Pythia simulations

- Pythia e-p at √s = 145 GeV (21 GeV electrons + 250 GeV protons)